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Acceptance of fluorescence detectors for photons and its implication in energy spectrum inference at the highest energies

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In this article, we investigate the acceptance of fluorescence telescopes to different primary particles at the highest energies. Using CORSIKA shower simulations without and with the new pre-showering scheme, which allows photons to interact in the Earth magnetic field, we estimate the aperture of the HiRes-I telescope for gammas and protons primaries. We calculate the dependence of the telescope sensitivity to primary particle identity. We also investigate the possibility that systematic differences in shower development for hadrons and gammas could mask or distort vital features of the cosmic ray energy spectrum at energies above the photo-pion production threshold. The impact of these effects on the true acceptance of a fluorescence detector is analyzed in the context of top-down production models.

1. Introduction

Top-down acceleration models, under very general conditions, should produce a sizable signature of primary gammas. The theoretical spectrum for such mechanisms shows an increase in the flux for energies above $10^{19.5}$ eV which could smooth away the GZK cut-off of the hadronic component. HiRes [1] and AGASA [2] experiments have explored the fluorescence and the ground array experimental techniques, respectively, to measure extensive air showers. Although AGASA shut down operations in 2004, its results are still essential to investigate the ultra-high energy cosmic rays. AGASA and HiRes have reported considerable differences regarding the primary cosmic rays spectrum around the GZK energies.

The ground array efficiency is based on a straightforward detection given by its operational area which is, in principle, not dependent on the primary particle type. On the other hand, fluorescence telescopes measure the longitudinal air shower development by detecting the fluorescence light emitted along the track of particles in the atmosphere. Particles with different mass induce showers with distinct longitudinal evolution in the atmosphere and for this reason the efficiency of fluorescence telescopes depends on the primary shower composition.

Since the original proposal of the Gaisser-Hillas function [3], many studies [4, 6] have shown that the number of charged particles (N) in hadron-initiated showers as a function of the atmospheric depth (X) is well described by a four parameter ($N_{\max}$, X_0, $X_{\max}$ and λ) function. Recently, a physical process has been shown to play an important role in the development of gamma-induced showers. Primary gammas with energies above 10^{19} eV can be converted into an electron-positron pair in the geomagnetic field before entering the Earth atmosphere. The resultant electron-positron pairs can lose their energy by emitting photons due to magnetic bremsstrahlung. If the energy of the subsequently emitted photon is high enough, another electron-positron pair can be created. Hence an electromagnetic cascade (pre-shower) is originated and will reach the Earth atmosphere instead of the primary high-energy primary photon. The pre-shower effect is significant for the development of the gamma shower in the atmosphere, substantially modifying its longitudinal development and making it look more similar to a nucleon-induced shower.

Fig. 1 shows the $X_{\max}$ distribution of 100 proton and gamma initiated showers. The influence of the pre-

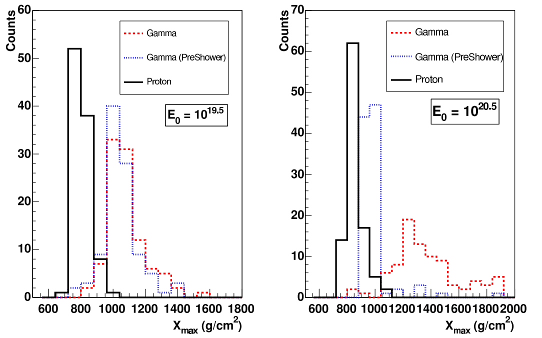

Figure 1. Distribution of $X_{\max}$ for showers initiated by protons and gammas with and without pre-shower. Results are shown for 100 showers at 45° zenith angle and energies of $10^{19.5}$ and $10^{20.5}$ eV.

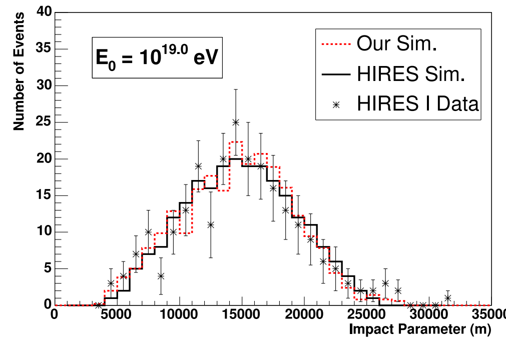

Figure 2. Distribution of impact parameters for showers at primary energies of 10^{19} eV. We compare our simulation with HiRes-I data and simulation

shower effect on gamma showers is illustrated by the $X_{\max}$ distribution at $10^{19.5}$ (left panel) and $10^{20.5}$ eV (right panel). At $10^{19.5}$ eV the $X_{\max}$ distributions for gamma showers with (dotted line) and without (dashed line) the pre-shower are almost identical and we can verify a not significant reduction of the average $X_{\max}$ distribution value. However, at $10^{20.5}$ eV the pre-shower influence is easily perceived, producing a quite reasonable difference between the $X_{\max}$ distributions obtained by simulations with and without the pre-shower effect.

2. Shower and Detector Simulation

In this contribution we used Monte Carlo simulations to evaluate the HiRes-I telescope aperture, following in detail the general specifications published by the HiRes collaboration in [4].

According to the HiRes collaboration procedures, we have performed a very detailed simulation of the cosmic ray air shower and the HiRes-I telescope. Proton and gamma ray showers have been simulated with the well tested CORSIKA [7] code, using the QGSJet hadronic interaction model [8], for the energy range 10^{19}-$10^{20.5}$ eV, in steps of 0.1 dex. For each energy and primary particle we have generated 100 events. A recent release of CORSIKA (version 6.2) implements the pre-shower effect [9]. For gamma ray showers, we have simulated two sets: a) with the pre-shower effect b) without the pre-shower effect. In order to save computation time, each CORSIKA simulated shower has been recycled several times by randomly drawing zenith angles and core positions.

The HiRes-I telescope has been simulated with a specific simulation program which calculates the number of fluorescence photons along the shower path, from the longitudinal development of the charged particles simulated by CORSIKA, and propagates the photons through the telescope. Fig. 2 shows a comparison between our simulation program and the HiRes-I data and the HiRes collaboration simulation. It is possible to verify the good agreement between our simulation and the HiRes data, showing that we are able to reproduce the most important features of the detector. The HiRes data and simulation have been extracted from [4]. We have calculated the impact parameter of the showers detected by the telescopes. The number of simulated showers was normalized to the number of detected events.

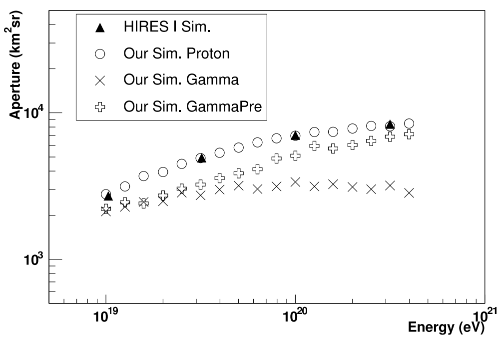

Figure 3. HiRes-I telescope aperture calculated by the HiRes-I collaboration and published in reference [4], calculated with our analysis program using shower generated by the CORSIKA code.

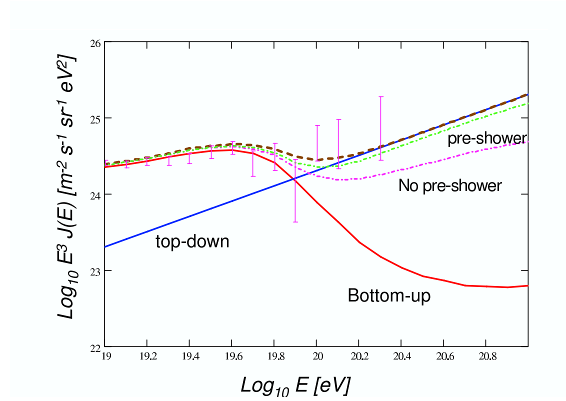

Figure 4. Cosmic ray spectrum as seen by the HiRes-I telescope for different primary particles and production scenarios.

3. Reconstruction and Analysis

The reconstruction of the showers also followed in detail the particular procedures described in references [4]. Basically, the inverse process described in section 2 is applied to reconstruct the shower longitudinal profile and consequently its energy. The number of photoelectrons measured in each pixel of the detector is mapped backwards onto the number of photons in the telescope, the number of photons in the axis of the shower and, finally, the number of particles in the shower. The telescope efficiency, atmospheric absorption, fluorescence yield and missing energies have been considered according to section 2 and references there in.

A Gaisser-Hillas [3] function was fitted to the data in agreement to the specifications in reference [4]. The $X_{\max}$ parameter was allowed to vary in 35 g/cm^2 steps between 680 and 900 g/cm^2. The X_0 parameter of the Gaisser-Hillas was fixed to - 60 g/cm^2, in conformity to reference [5]. Quality cuts are always needed to ensure an accurate reconstruction. We have required events to satisfy the conditions listed below as taken from reference [4]: 1) Average number of photoelectrons per phototube greater than 25; 2) Angular speed less than $3.33°\quad \mu s$; 3) Track arc-length greater than $8.0°$; 4) Depth of first observed point less than 1000 g/cm^2; 5) Angle of the shower in the plane containing the shower axis and the detector greater than $120°$. Showers which did not obey those conditions were rejected, and excluded from further analysis.

4. HiRes-I Telescope Aperture and Spectrum

We have investigated the dependence of the aperture on different primary particles. According to [4] the HiRes collaboration has determined the spectrum based only on aperture investigations of the HiRes-I telescope for proton and iron showers.

Fig. 3 shows the aperture for proton and gamma initiated showers (with and without the pre-shower effect). In all curves, we have used 100 different showers shuffled 50 times each as explained before in section 2.

If the pre-shower effect is not taken into account, gamma showers tend to develop much deeper in the atmosphere when compared to proton induced showers. This fact makes gamma ray showers harder to detect, which represents a great reduction in the telescope aperture for all energies.

When the pre-shower effect is considered, gamma showers with energy above $10^{19.5}$ eV have a considerable probability of conversion into a electron-positron pair (more than 5%) [9]. The probability conversion increases very rapidly with increasing energy and reaches 100% between $10^{20.0}$ and $10^{20.5}$ eV depending on the arrival direction of the particles related to the Earth magnetic field. The aperture calculation shown in fig. 3 illustrates this increase of the conversion probability. Gamma showers simulated with the pre-shower effect evolve from a "gamma without pre-shower profile" to a "hadronic profile" with energies varying from $10^{19.5}$ to $10^{20.6}$ eV, which make the HiRes-I aperture for gamma ray showers close to aperture for the hadronic showers.

Despite the fact that the conversion probability of a gamma in the Earth magnetic field reaches 100% at $10^{20.6}$ eV, the HiRes-I telescope aperture for gamma ray showers is smaller than the aperture for proton showers.

5. Astrophysical significance

The fact that the HiRes aperture has been calculated under the assumption of hadronic primaries, opens the possibility of the existence systematic effects for a broad range of cosmic ray production scenarios. In particular, it cannot be disregarded at present the possibility of mixed extragalactic components: a hadronic one, coming from conservative bottom-up acceleration mechanisms and a photon, harder component originated in more exotic top-down models.

As an example, figure 4 illustrates such a combination of spectra. The GZK-ed spectrum (lower thick line) has been numerically calculated using a homogeneous distribution of cosmological sources whose luminosity evolves with redshift according to $(1+z)^m$ with $m = 3$. Protons were injected at the sources,with a power law spectrum (spectral index $\nu_i = 2.7$ and energy loses due to redshift, pair creation and photo-pion production in interactions with the cosmic microwave radiation are included. The resultant spectrum is normalize to the AGASA observed flux at 10^{19} eV. The normalization of the harder (spectral index $\nu_{TD} = 2$) top-down spectrum is such that trans-GZK AGASA data can be fitted by the combined spectrum (thick dashed line).

The dot dashed curves illustrate the spectrum that HiRes would infer for the case of a photon component described with and without pre-showering. It can be seen that in the case without pre-shower the effect could be severe enough as to make AGASA and HiRes spectra compatible within quoted uncertainties. The existence of pre-showers considerably diminishes this effect, maintaining unaltered the AGASA-HiRes discrepancy.

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